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WRITTEN REPORT / CREATIVE INVESTIGATION

THE LEO DEBRIS PROBLEM: A REENTRY SOLUTION ANALYSIS

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MAY 20, 1998

ABSTRACT

Since the beginning of the Space Age, thousands of man-made objects have been placed into orbit around the Earth. The number of objects in low Earth orbit (LEO) is continuing to increase, and overcrowding is becoming critical. This report focuses on the problems facing spacecraft in LEO and gives findings of a modeling study on reentry survivability, measured findings, and recommendations for improvements.

The methodology of the modeling study is presented along with the results. Variables such as type of material, mass, and mode of spinning/tumbling are evaluated. The objective of this section is to determine the point of demise (burn-up) or survivability of the object.

The next section presents measured findings of a study on 331 reentries of inactive spacecraft, expended upper stages, and spacecraft deployments from September 1992 to December 1996. This study was conducted, in part, to determine if impact zones were found to be essentially uniform in terms of latitude and longitude.

The results of these two sections on reentry, along with a review of the legal ramifications involved in reentry, were used to recommend the use of de-orbiting to lessen the amount of debris in LEO. Additionally, this report presents specific guidelines on possible solutions to the problem, along with the benefits and drawbacks of each.

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BACKGROUND

In recent years, the problem of increasing global population has put a particular strain on managing waste. While landfills are overflowing on the ground, a similar situation is evolving in space. The drive for technology and discovery continues to expand our interest in the cosmos. Whether improving communication or photographing the world's land masses, satellites have proven useful in many areas. Unfortunately, these spacecrafts have also introduced new problems.

While the amount of space surrounding the Earth seems limitless, it is in fact becoming quite crowded. Specifically, the low Earth orbit (LEO) area is cluttered with space objects and will soon be occupied with even more, as large constellations are approved. There is an increasing need to identify solutions to the overcrowding in LEO before the situation becomes critical.

Current regulations on reducing orbital debris are weak at best, and companies who choose to limit debris are not rewarded for their actions. This paper identifies a solution to the LEO debris problem and an analysis of its ramifications. By statistically analyzing the probability of reentry survival of different types of satellites, it is possible to recommend certain end-of-life disposal activities. Further study may encourage stronger

regulations or incentive programs for mitigating orbital debris in LEO.

The Orbital Debris Problem

When Russia launched Sputnik I in October of 1957, they put the first man-made object in space. Since that time, thousands of objects have been sent into orbit around the Earth. There are currently over 9000 objects (larger than 10 cm^2) being tracked by the U.S. Space Command Space Surveillance Network. These objects include active and inactive payloads, spent upper stages, and fragmentation debris from more than 140 on-orbit collisions.[1] Whether a giant satellite or a tiny speck of paint, orbital debris poses numerous hazards. Although the probability of collision between an operational space asset and a piece of debris is quite small, the potential losses can be very high. The velocity of LEO satellites, those at less than 300-500 km altitude, is about 7 km/sec, and the relative velocities of two objects at LEO can be as high as 12-14 km/sec (nearly 30,000 mph).[2]

While the current problem of orbital debris is real, it has not reached a severe level. However, if past trends continue, the number of tracked objects in space is predicted to double within the next 20 years. This increase will result in more collisions and, consequently, more

debris. The predicted high frequency of collision will propagate an irreversible growth in fragment population. Such an increase will make orbiting in space treacherous and often fatal to satellites. The following graph describes the increase in orbital debris and projects the cumulative number for the future: [3]

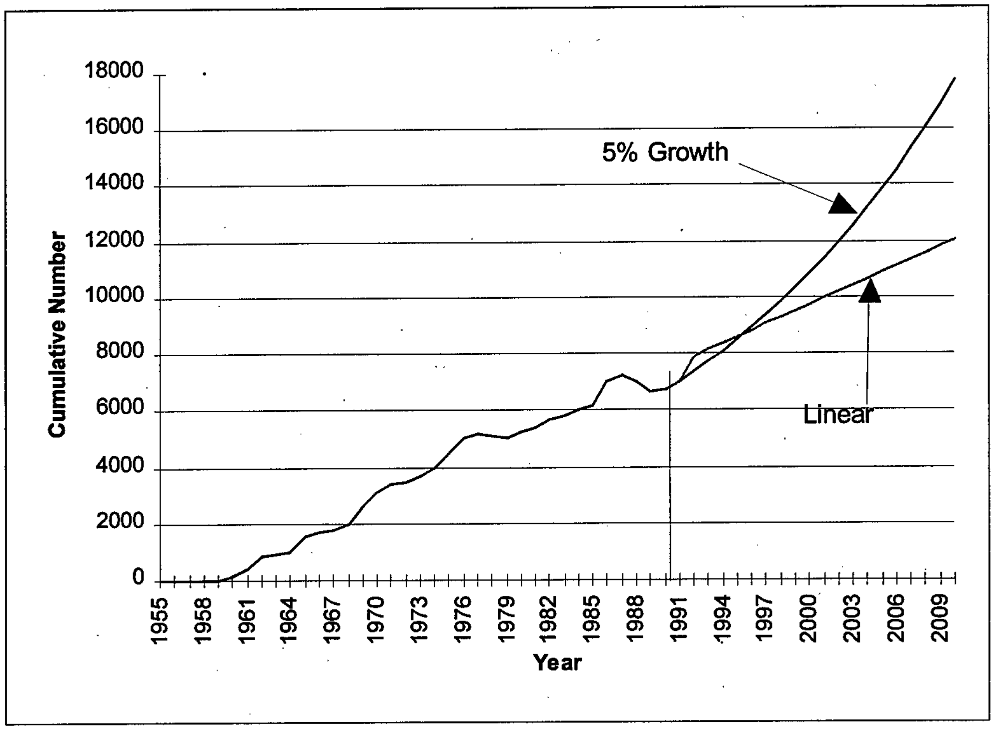

Figure 1
Projected Growth of Cataloged Debris (larger than 10 cm^2)

In order to estimate the amount of debris in space, scientist have run many experiments and produced several models. One particularly useful experiment was the Long Duration Exposure Facility (LDEF) satellite. This spacecraft flew in LEO for 69 months and returned to Earth for evaluation. About 20,000 craters were measured to estimate the natural and man-made debris environments to

which LDEF was exposed. Although most of the impacts were small, the largest impact formed a crater just over 5 mm in diameter. This crater was estimated to have been caused by a piece of debris about 1 mm in diameter.[4] This experiment highlights that fact that small debris is in abundance in space and has the potential to damage numerous satellites.

The orbital debris environment is increasing with time and represents a growing risk to future space programs. Since the Space Station is about to begin assembly, the interest in preventing orbital debris grows every day. Studies predict that the Space Station (5000 m^2 at 400 km altitude, 51.6 degree inclination orbit) will have one collision with an object larger than 1 cm every 71 years. This prediction will certainly grow as more objects enter space and collisions occur. The problem will affect many aspects of spacecraft development in the future.

LEO Constellations on the Rise

Contributing to the clutter in LEO are many recently approved constellations for the growing business of personal communications. Due to the increase in demand for mobile telephone services, many companies are looking to space for an answer. Motorola was the first company to begin development of such an idea. By the late 1980's, Motorola converted their vision into a $5 billion project called

Iridium.[5] Today, there are nearly half a dozen similar projects in the works.

The benefits of satellite communication greatly outweigh the costs. While fiber optics may prove cost effective in urban areas, satellites bring wireless communication to vast regions of the globe - even the most remote. This technology is making space a solution for a wide range of telecommunication needs, from simple paging to complex Internet or video transmissions.

The current interest in LEO communication brings to light some of the shortcomings of satellites in geosynchronous Earth orbit (GEO). For some 30 years, GEO has been the orbit of choice for data and television transmission. However, GEO launches are extremely expensive and problems such as voice delay and limited capacity make it less than ideal for personal mobile communications.[6] The interest, therefore, turns to satellites in a lower orbit.

Motorola's Iridium project is just one of many mobile communications systems proposed in recent years. Dozens of military and civilian projects will be launched into low or medium orbits over the next few years. Adding to the traffic will be such constellations as Globalstar (48 satellites), Orbital Science (36 satellites), and GE Americom (24 satellites). Each of these satellites will present a separate risk to LEO traffic. Iridium, for

example, will contain a constellation of 66 satellites, each about 1,500 pounds, at an altitude of 420 nautical miles.[7] The constellation is expected to be complete and operation before the end of the century. There is a huge demand for wireless communication, and that demand may be met in space.

Existing Regulations

Over the past four years the Federal Communications Commission (FCC) has authorized nine medium to low Earth orbit communication constellations. All of these constellations were authorized without coordination by the FCC of the orbital planes and altitudes and without guidelines for collision avoidance. Additionally, the FCC has refrained from regulating end-of-life disposal for these satellites. This lack of policy opens the door to various disposal procedures - from active de-orbiting to virtually no action at all.[8]

On the other hand, the Federal Aviation Administration's Associate Administrator for Commercial Space Transportation (AST), which regulates commercial launch vehicles, has proposed new regulations to ensure uniform debris mitigation measures. AST will require launch licensees to adopt vehicle designs and launch procedures to ensure that spent upper stages do not fragment and generate debris.

Besides the FCC and AST, the 1996 U.S. Government space policy requires "all space sectors to minimize the creation of orbital debris consistent with mission requirements and cost effectiveness." Additionally, the Department of Defense (in particular the Air Force and the U.S. Space Command) has, since 1987, practiced orbital debris minimization. Both DOD and NASA are consistent with the national orbital debris policy.[9]

These four regulators have taken different approaches to mitigating orbital debris. While AST has relatively clear guidelines on spacecraft design, the FCC, DOD, and NASA have published only broad regulations about minimizing debris. It is evident that if the government and space agency continue to avoid an active role in managing the physical aspects of LEO constellation operations, the problem of orbital debris may produce many undesired consequences.

INTRODUCTION

Due to the increasing danger of orbital debris, proactive measures must be studied to help relieve the situation and continue to allow further use of space property. The analysis included in this report will present findings on reentry survivability and statistical studies of various entry possibilities. The review will first relate theoretical findings from computer models and simulation. After discussing the methodology and assumptions, the report focuses on the statistical findings generated by the studies. This information covers topics such as materials used in different spacecrafts as well as their position during reentry.

The second part of the analysis presents measured findings on reentry. It relates the results of a study on 331 reentries of inactive spacecraft, expended launch vehicle upper stages, and associated hardware that occurred from September 1992 - December 1996. This study focused on the point of reentry to help develop more accurate forecast models. Results from this study should help researchers predict to what extent and where various debris will reenter.

The final part of the analysis includes a review of the legal aspects surrounding space debris and reentry. This section focuses on liability issues when spacecraft reenter

the Earth's atmosphere and land on the surface. It also discusses the command and control aspects of regulation, as well as the funding involved in requiring de-orbit from LEO. In proposing a de-orbiting solution to LEO debris, the legal ramifications are very important.

After presenting the information available, this report offers several recommendations. Besides the use of a regulatory committee to set guidelines and ensure compliance, an incentive-based approach may also prove useful. Both of these possibilities are discussed, as well as their benefits and drawbacks. While many solutions may exist to combat the LEO debris problem, this report focuses specifically on de-orbiting satellites at end-of-life.

REENTRY SURVIVABILITY MODELING

Since atmospheric drag is the only natural mechanism for removing orbital debris, it is important to understand and evaluate its consequences. If regulating authorities decide to require certain satellites in LEO to de-orbit at end-of-life, they must analyze the implications of such a requirement. Hardware reentry survivability must be evaluated to assess risks to human life and property on the ground. This section presents findings on issues such as altitude of demise or survivability of reentering objects.[10]

Methodology

The findings presented on the trajectories, aerodynamics, aerothermal environment, and thermal response of selected spacecraft components are from two NASA/JSC computer codes - Object Reentry Survival Analysis Tool (ORSAT) and Miniature ORSAT (MORSAT). These codes were validated by closely predicting demise altitude of a Sandia fuel rod undergoing orbital decay, according to the measured results. A short summary of five general areas (models) of the code are presented below and are categorized as: trajectory/atmosphere model, aerodynamics model, aerothermodynamics model, thermal analysis and demise model, and reentry risk analysis model.

The trajectory model had two options for analysis - targeted entry and entry from decaying orbits. The targeted entry allows the prediction of hardware impact locations on the Earth without assessing the reentry survivability (i.e., predicting the heating loads on the object). For either entry option, a 3-degree-of-freedom trajectory was computed using four equations in an Earth-fixed reference frame: time-rate of change of altitude, longitude, relative velocity, and flight path angle.*

The aerodynamics model was used to improve the accuracy of the trajectory model. In the trajectory equation for relative velocity, there is a term that includes the drag force (with the drag coefficient, C_D). Depending on the shape of the body and the flow regime (continuum, transition, or free molecule), the drag coefficients in the codes were computed by various means. For example, the value of C_D in the continuum regime for spinning cylinders entering broadside is 1.22, and in free molecular flow, it is 2.0. Other drag coefficients may be drawn from variations of a sphere.

The aerothermodynamics model dealt mainly with the hot and cold wall heat rate. The net heating rate to an object is equal to the hot wall heat rate (which is a function of

* These equations are derived assuming a spherical, rotating Earth.

the cold wall heat rate) plus the oxidation heat rate minus the reradiation heat rate:

$$\text{Heat}_{\text{NET}} = \text{Heat}_{\text{HOT WALL}} + \text{Heat}_{\text{OXIDATION}} - \text{Heat}_{\text{RERADIATION}}$$

The average cold wall heating rate was computed as the stagnation point heat rate for a sphere and then multiplied by a factor which accounts for the type of body (sphere, cylinder, flat plate, or box). The oxidation heat rate was based on an empirical constant times the cold wall heat rate times the oxide heat of formation. Finally, the reradiation heat rate was a function of wall temperature to the fourth power times the material surface emittance. Therefore, the higher the emittance, the lower the net heat rate, and better the chance of survival.

The thermal analysis and demise models were useful in determining the burn-up point of the object. Two methods were used to obtain the surface temperature and point of demise of the object: the lumped mass model and the nodal thermal math model. The lumped mass model is used with MORSAT because it is the quickest to use, and the more accurate nodal thermal math model is used only with ORSAT. Unlike MORSAT, the nodal thermal math model may show a surface temperature drop after the melting temperature is removed if the net heat rate to the surface is decreasing.

The fifth and final model used in this study was the reentry risk analysis model. For objects that survive reentry, the debris area was computed by using the maximum cross sectional area of the object and adding a 0.3 m border. The total debris area equaled the sum of the individual fragment areas that have broken off the original parent body. The expected number of casualties, or risk, equaled the probability of impact on land mass times the population of the land area in the latitude band time the debris area divided by the land area:

$$\text{Risk} = [\text{P(impact)} \times \text{Population} \times \text{Debris Area}] \div \text{Land Area}$$

By using all five of these models, along with certain assumptions, several interesting results were uncovered.

Assumptions

This section presents the principal assumptions used in the 6-month investigation, including a review of a parametric study on spheres and cylinders of variable materials undergoing orbital decay. Variables for the spheres include mass, diameter, wall thickness, and ballistic coefficient. The variables for the cylinders additionally include four modes of tumbling and/or spinning. Five materials were considered in the study: aluminum, copper, stainless steel, titanium, and beryllium.

A parent object for all fragments consisting of a sphere of diameter 1.852-m with mass 1300 kg was used. A breakup altitude of 78 km was assumed for all objects. In some cases, results from ORSAT were used to compare with those of MORSAT.

The study also evaluated two pieces of a Delta II 2^{nd} stage rocket: a stainless steel cylindrical propellant tank and a titanium helium-pressurization sphere. The parent body was assumed to be the Delta 2^{nd} stage empty cylindrical tank with a length of 5.97 m, diameter of 2.44 m, and mass of 919 kg. The MORSAT and ORSAT codes were run to determine the entry conditions and survivability of the two fragments. The results were then compared with actual findings of these two pieces that entered the atmosphere on 22 January 1997, and survived.

Results

By using the above-mentioned models, several important results were presented. First, the models illustrated that the ability of a space object to survive reentry and strike the surface of the Earth is highly dependent upon its design and composition. Materials such as titanium and stainless steel possess a greater likelihood of surviving than do aluminum and copper (Figure 2). Although beryllium was considered in the study, it does not appear on the graph

since spheres of beryllium survived even at the smallest diameters.

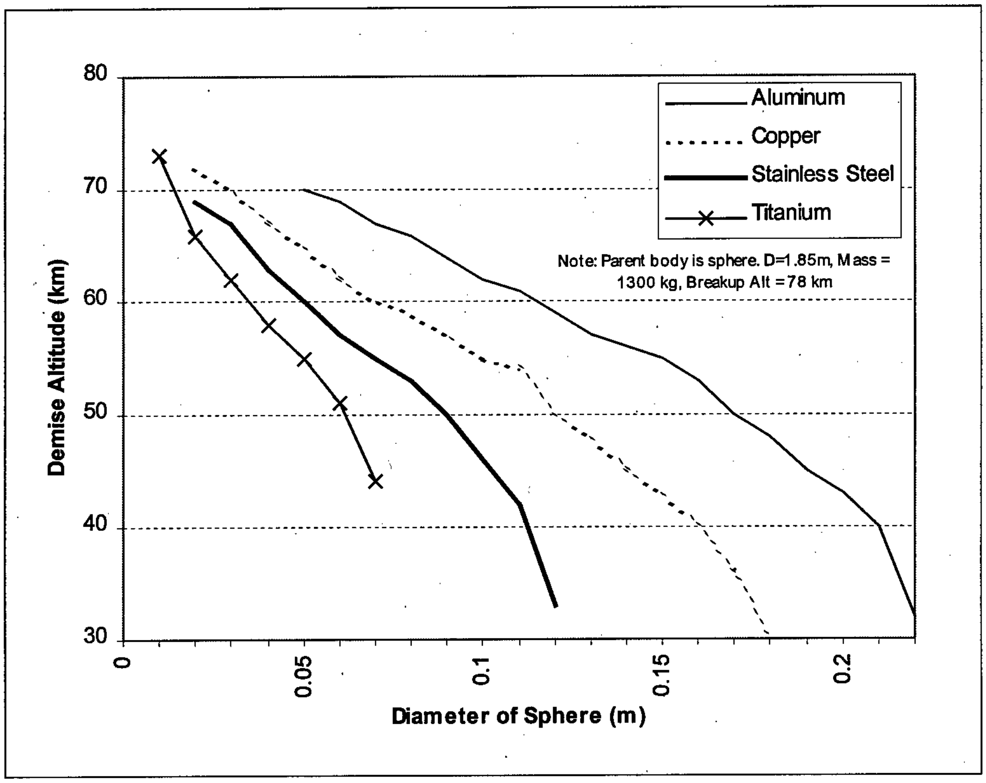

Figure 2
Demise Altitude vs. Diameter for Solid Spheres of Various Materials

Besides composition, the design of a spacecraft may also affect its survivability. In the case of a cylinder, the highest altitude of demise occurs when the cylinder's end is perpendicular to the reentry path. The end-on spinning case causes the heating to be applied only on the front face and not distributed over the body. When the satellite was tumbling or otherwise rotating, heat was distributed much more evenly, causing a lower altitude of demise (if it occurred at all). Figure 3 shows the demise

altitude as a function of cylinder thickness given various tumbling or spinning positions.

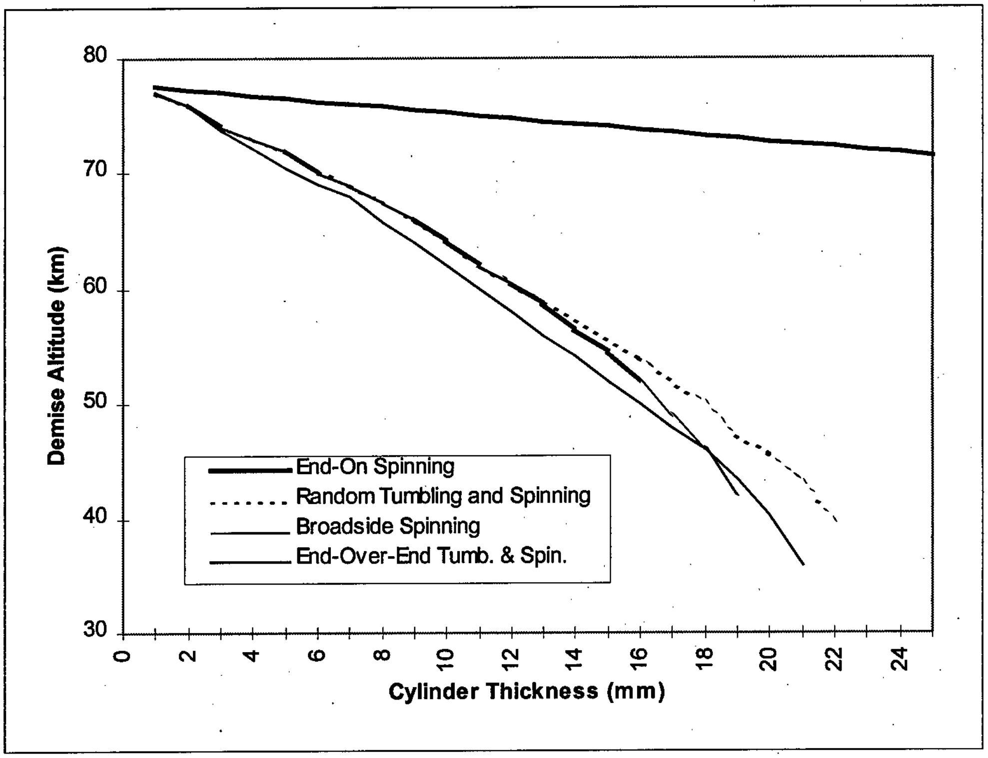

Figure 3
Demise Altitude vs. Cylinder Thickness for 0.5 m Diameter, 3.0 m Long Aluminum Cylinder

Results from the Delta 2nd stage analysis were extremely close to the actual findings. The two analyzed fragments were predicted to survive and land within 35 km of the actual difference in location between impact points of what actually happened. The sphere was traveling at a faster velocity, higher altitude, and less negative flight path angle. Thus, the sphere would be expected to land at a farther location than the cylinder, which it did.

MEASURED FINDINGS OF REENTRY

While the previous section presents results from a modeling study of reentering debris, this section will present measured findings of reentry over a period of time.[11] The study examined 331 reentries of inactive spacecraft, expended launch vehicle upper stages, and associated hardware from September 1992 - December 1996.

Since the Sputnik I launch vehicle decayed from orbit on 1 December 1957, approximately 16,000 space objects, ranging from 10 cm to 25 m in length have also reentered (Figure 4). Thousands more objects are known to have also decayed, though they were not officially cataloged.

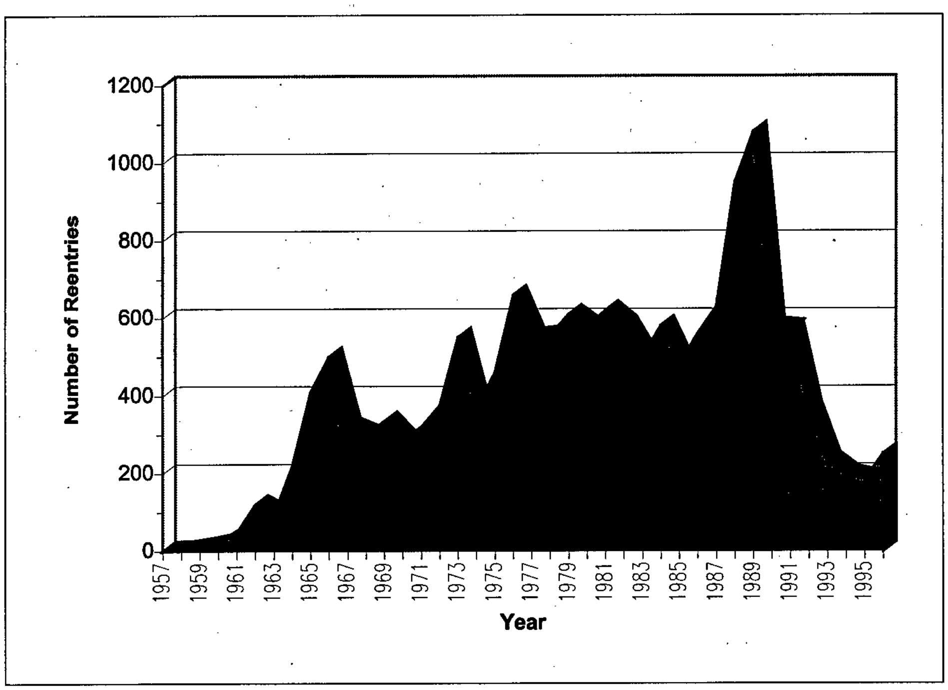

Figure 4
Annual Number of Cataloged Satellite Reentries*

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* The period from September 1992 to December 1996 coincided with a minimum in solar activity and a reduction in global launch rate and, therefore, a marked reduction in natural reentries.

Since most small debris usually burn up in the upper atmosphere, and never reach the ground, emphasis is placed on the consequences of the reentry of large orbital debris. The NASA guideline on reentry debris recommends limiting the total casualty area of surviving debris to 8 m^2 per event. This value is linked to an average risk of human casualty of no more than 0.0001 per reentry event. Based on these risks, the purpose of this study was to determine if natural reentries of large orbital debris are uniformly dispersed over the globe, taking into account inclination/latitude restrictions.

The U.S. Space Command executes a reentry assessment as standard operating procedure for objects with a radar cross-section of 1 m^2 or greater. This process usually begins 1-2 weeks prior to the initially projected reentry date, and predictions are updated until the event occurs.* While this technique is sometimes useful, it is often incorrect. Unfortunately, the capability to predict accurately the time and location of natural reentries does not yet exist. Although technology has not yet produced a method of predicting reentry characteristics, it can help analyze current data and perhaps offer a sketchy model of reentry.

The 52-month study from September 1992 to December 1996 yielded some useful results on reentry survivability and may

* The frequency and accuracy of the prediction time increases as reentry approaches.

pave the way for more accurate models. During this period, approximately 950 reentries occurred, 100 of which were directed de-orbits using propulsive maneuvers. Of the remaining 850 natural reentries, more than half fell below the 1 m^2 threshold for assessment by the Space Command. There were 331 objects remaining to be analyzed - 46 spacecrafts, 180 upper stages, and 105 miscellaneous debris.

An examination of the reentry locations of these objects showed that about 56.6% landed in the Northern Hemisphere and the remainder in the Southern Hemisphere. The following chart displays the breakdown by category of reentry location distribution:

Category of Debris	**Northern Hemisphere**	**Southern Hemisphere**
Upper Stages	56.7%	43.7%
Payloads	43.5%	56.5%
Unclassified Debris	61.9%	38.1%

Further analysis showed that objects with lifetimes less than 30 days tended to end up in the Northern Hemisphere 62% of the time. This asymmetry can be attributed to the fact that all space launches during the period were from Northern Hemisphere sites. Also, a considerable majority of short-lived space objects possess initial arguments of perigee in the Northern Hemisphere.

Objects with longer lifetimes were equally distributed over the two hemispheres. The older orbital debris possesses a more uniform distribution of arguments of perigee and, hence, a more even distribution of reentry points.

The latitude area of reentry is a function of the argument of perigee as well as the orbital inclination. The Northern Hemisphere bands from 0-45 degrees witnessed over 40% of the reentry locations (Figure 5). Although the majority of the world's population resides between these latitudes, the danger to humans may not be that large since the actual impact points of surviving debris tend to be several hundred kilometers from the calculated reentry point.

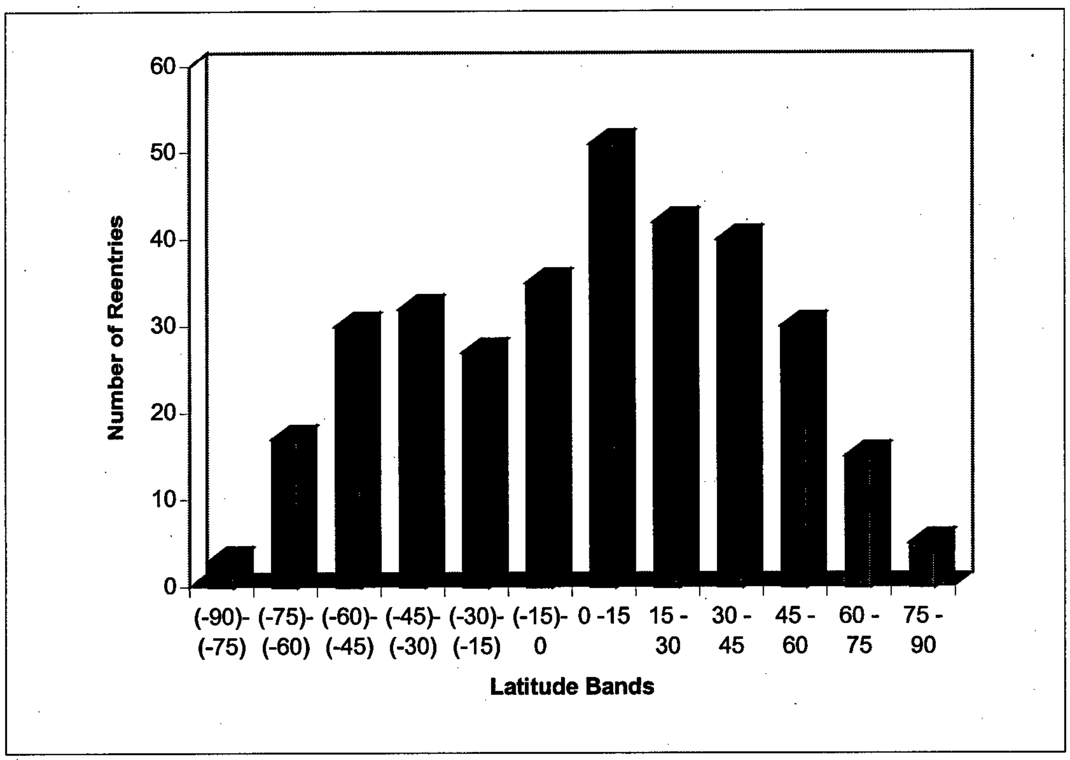

Figure 5
Large Orbital Debris Reentry Locations by Latitude Bands

Of those objects that do reach the surface, more than 70% will impact bodies of water. Even objects that hit land will probably come to rest in sparsely populated regions, due to their vast expanses.

This study verified historical assumptions of random reentry by naturally decaying satellites in Earth orbit for more than 30 days. However, for objects in orbit less than 30 days, which was nearly 51% of all large debris studied, the preference for reentry was the Northern Hemisphere. Additionally, no apparent effects of atmospheric or gravitational variations were found. This information will help revise some of the older models and continue to improve reentry predictions, especially for debris in orbit less than a month.

The accuracy of reentry propagation is inadequate to support precise impact predictions. The problem arises in trying to determine the reentering object's attitude and stability, as well as variations in the atmospheric densities. Even a small error, on the order of minutes, may cause a difference of a thousand kilometers in the impact location. With the increase in LEO traffic, it will become increasingly important to life and property to accurately predict the level of survivability and location of impact for reentering objects.

LEGAL ASPECTS OF DEBRIS MITIGATION

The results of the analysis on debris reentry suggest that de-orbiting LEO satellites at their end-of-life is a feasible option with few adverse impacts on the ground. However, the legal aspects of such a mandate require close examination. The legal approach, deriving expert advice from the engineering community, uses legislation and administrative orders and regulations to impose solutions. The technical approach, on the other hand, aims at establishing standards and recommended practices for design. Unfortunately, only minimal policies on either end exist.[12]

If satellites in LEO were required to de-orbit as a disposal technique, several factors must be considered. First, with such an increase in the number of intentionally reentering objects, specific guidelines must be established concerning liability for damage caused. The convention in 1971 that outlined liability for damage caused by space objects stated that "a launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft flight.[13]" In order to comply with this agreement, nations must enforce strict tracking of their space objects and have solid evidence of liability. Despite the considerable number of reentries of large orbital debris in the past, no case of

personal injury caused by reentering debris has been confirmed.[14]

Besides determining liability, it will be important to establish a centralized command and control agency. The agency should be responsible for monitoring and regulating certain space activities, as well as punishing those not in compliance. Although current guidelines aim at reducing orbital debris, they are very weak in the area of enforcement.

A final area of interest in requiring satellites to de-orbit from LEO is funding. If the measure becomes a mandate, an important question for non-profit and educational satellites will be how to pay for the additional fuel and structure required to intentionally reenter. Such groups already work on tight budgets and may have difficulty meeting the additional requirements. In order to allow these groups to continue their work, it may be necessary to help fund any additional costs associated with the new regulations.

RECOMMENDATIONS

Based on the findings mentioned in this report and certain observations on LEO debris, it is apparent that several solutions may exist to reduce the orbital debris problem. One solution may be a command and control approach, as mentioned in the previous section. NASA and DOD could jointly develop draft design guidelines that could serve as a baseline for agency requirements of future spacecraft and launch vehicle/service procurements. After completing an initial draft of such guidelines, they should then seek review from outside agencies and individual experts. A workshop may convene to further discuss the guidelines and compromise on key issues. The most important product of such an approach would be solid, tangible limits on design and de-orbiting, since vague regulations only lead to confusion and noncompliance.

An important component of these design standards may involve composition materials. As shown previously, titanium, stainless steel, and beryllium decompose much slower during reentry than aluminum and copper. By limiting the amounts of these more durable metals, NASA and DOD may eventually reduce the risks associated with de-orbiting. Additionally, spacecrafts may be required to enter the atmosphere in a stable position, since spinning objects were shown to burn up slower.

This command approach to limiting LEO debris has several drawbacks. By mandating technology, instead of performance, the government may stifle innovative solutions. Engineers across the country are renowned for their ability to think out of the box, and specific regulations would certainly limit creative solutions. The regulatees will also witness an increase in the cost of their system, since such regulations almost certainly mean more expenditure. Besides the inconveniences placed on production, the government will also face challenges. In order to enforce these regulations, the government will have to create a regulatory agency, which will add more cost to the entire process.

Another approach to the problem capitalizes on innovation and creativity by offering economic incentives. Since businesses are always trying to save money and increase profits, they may be economically persuaded to manage orbital debris. For example, rather than requiring de-orbiting of launch vehicles or payloads, the government could require a launch deposit that is refundable with interest upon successful de-orbiting.[15] Another incentive-based example is to offer tax deductions to companies that do an exceptional job of limiting debris. The costs of such incentives would probably equal the costs of creating a regulatory agency to enforce regulations. In each case,

these incentive-based solutions give freedom to the regulatees on how to mitigate debris and may help develop new technology in the area.

CONCLUSION

Despite the large amount of orbital debris present in LEO, there is still hope for the future. Industry and government both recognize the problem and have been taking steps to correct it for the past several years. However, small steps will only delay the overcrowding. It will be very important to make fundamental changes to the way we use space, so that we may have these resources in the future.

The results of the studies presented in this report were useful in recommending several solutions to the LEO overcrowding problem. The most significant solution to orbital debris in LEO is de-orbiting satellites and expended upper stages. The results support the use of aluminum and copper over titanium, stainless steel, and beryllium to demise at higher altitudes. Also, stable spacecraft reentering the atmosphere will burn up at a faster rate than satellites that are spinning.

By designing LEO spacecrafts with the intent of de-orbiting them at the end-of-life, the amount of orbital debris will begin to decrease. Whether the government decides to enforce regulations on satellite disposal or offer incentives to reduce debris, it will need to act quickly and decisively. The problem of orbital debris will not disappear without a coordinated effort that is supported by the government as well as the entire space community.

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